Project Title: Ultra high efficiency thin film multi-junction solar cell
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Summary:

The Harris group proposed to develop significantly higher efficiency thin film multi-junction solar cells by combining multi-junctions and advanced nano-scale light management concepts in ultra-thin film devices that lend themselves to very large scale, low cost manufacturing. In the past year, they developed thin-film nanostructured solar cell modeling, epitaxial growth and fabrication. A nanostructured ultra-thin-film GaAs solar cell (300 nm) demonstrated improved Jsc, Voc, fill factor and efficiency. The voltage enhancement on a 5-µm-thick Si cell was demonstrated, which achieves a V_{oc} of 649 mV. They also developed bonding process and luminescent coupling modeling for multi-junction solar cells based on Si.

Key Accomplishments:

An ultra-thin-film 'nanowindow' solar cell (figure 1a, b) was developed that combines a nanostructured window layer with an ultra-thin-film (300 nm) planar absorber/junction. This ultra-thin cell consists of a nano-structured $Al_{0.8}Ga_{0.2}As$ window layer on the front side to reduce the reflection and to trap the light, and a metal reflector on the back side to further increase the light path. The 300 nm thick GaAs cell with $Al_{0.8}Ga_{0.2}As$ nano-window shows a broad band absorption enhancement from the visible to near infrared (NIR), achieving a spectrally averaged absorption of 94% under normal incidence (figure 1c). Different from the Fabry-Perot oscillations of the planar control sample, flat, broad-band absorption of the nano-structured sample is observed, which is a result of the more confined optical modes formed in the nano-structured film. In addition, this cell shows excellent angular absorption properties, achieving over 85% spectral averaged absorption at up to 60 degrees off normal incidence (figure 1d). Meanwhile, this structure with a planar junction and nano-window has solved the issue of poor fill factor and low open-circuit voltage in nano-structured GaAs solar cells. Because of the anti-reflection and light trapping of the nano-window layer, J_{sc} of the nanostructured cell is improved from 11.9 mA/cm^2 in the planar control sample to 13.8 mA/cm^2 for the nano-structured sample (figure 1e). The overall efficiency is increased from 7.41 % to 9.00 %.

In a second part of our high-efficiency solar cell development, we have focused on the voltage enhancement of thin-film c-Si solar cells due to vertical carrier confinement. The physical mechanism of vertical carrier confinement was theoretically studied with simulations (figure 2a). Furthermore, the voltage enhancement in a 5-µm-thick c-Si cell was experimentally demonstrated, which achieves a 9 mV higher V_{oc} than a 50-µm-thick cell (figure 2b). This is also the highest V_{oc} among recently reported sub-25-µm-thick cells. Together with the nanostructured dielectric layer (NDL) of SiN_x on c-Si, the overall energy conversion efficiency will be further improved. This work provides a solid foundation for the continued development of future high-efficiency and low-cost thin-film crystalline solar cells.

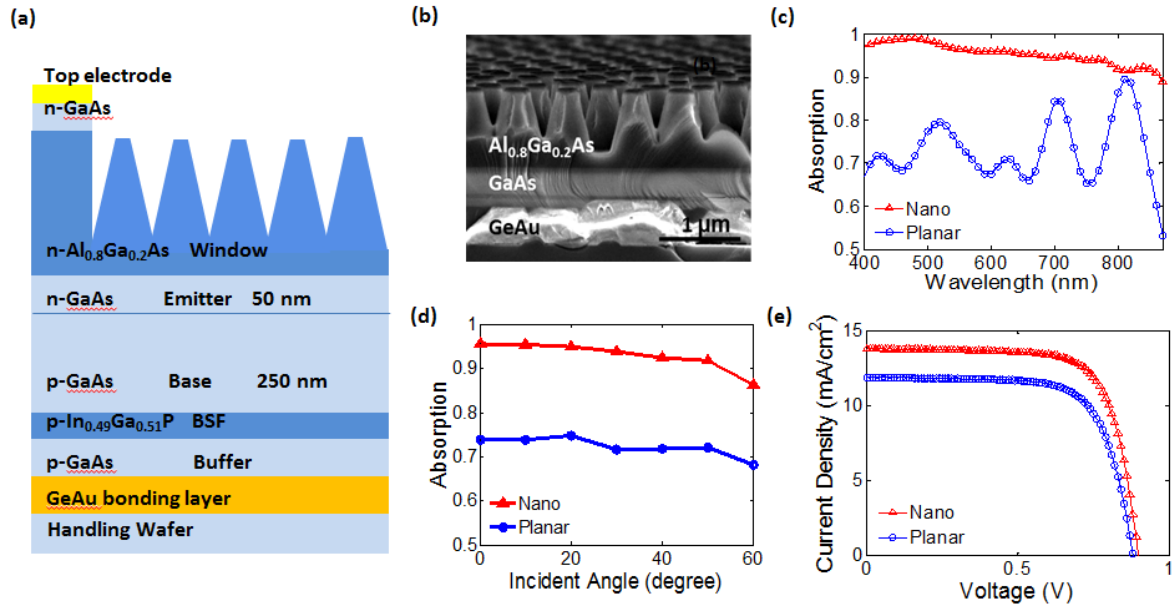

Fig. 1. Overview of the structure and measured characteristics of an ultra-thin-film AlGaAs/GaAs nanostructured window solar cell. (a) Schematic of the cell structure. (b) SEM cross-section image of the solar cell active region with $Al_{0.8}Ga_{0.2}As$ nanocone window layer. The GaAs solar cell is only 300 nm thick. (c) The measured absorption spectrum of ultra-thin-film GaAs cells with nano-window (red) and planar window (blue). (d) The measured spectrally averaged absorption versus incident angle of ultra-thin-film GaAs cells with nano-window (red) and planar window (blue), weighted by AM 1.5G spectrum. (e) J-V characteristics of the ultra-thin-film GaAs solar cells with nano-structured (red) and planar (blue) window layer.

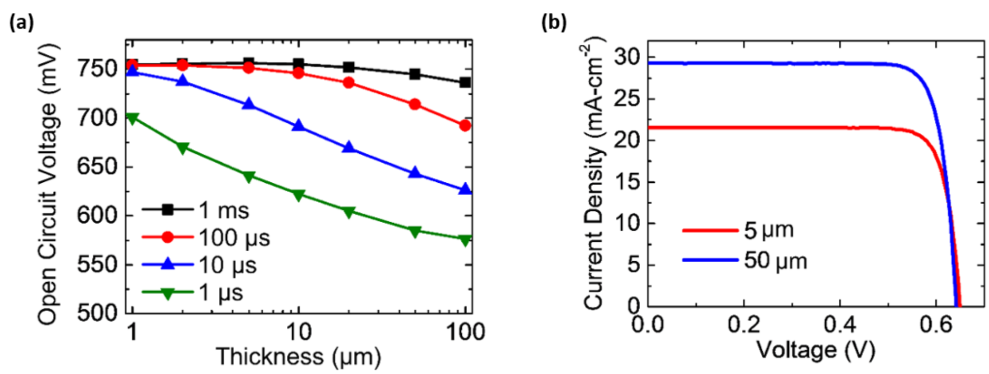

Fig. 2. Overview of the voltage enhancement of thin-film c-Si solar cells. (a) Simulation V_{oc} as function of cell thickness (W) and minority-carrier life time (τ). (b) *J-V* characteristics of 5-µm-thick and 50-µm-thick c-Si solar cells.

In addition, an In-Au metal bonding process has been developed to replace the Ge-Au bonding process. This bonding process lowers the bonding temperature to below 250°C, reducing damage to the ultra-thin film GaAs cell. Since indium forms a thinner, small bandgap layer rather than a very highly Ge doped region, this process also prevents the shunting effects caused by germanium diffusion and phase segregation. In-Au bonding of bulk materials has been demonstrated with very good bonding strength and uniformity (figure 3). Combined with the subsequent substrate-removal process, which is under development, this bonding process can produce a very promising pathway to a high-efficiency multi-junction device on c-Si.

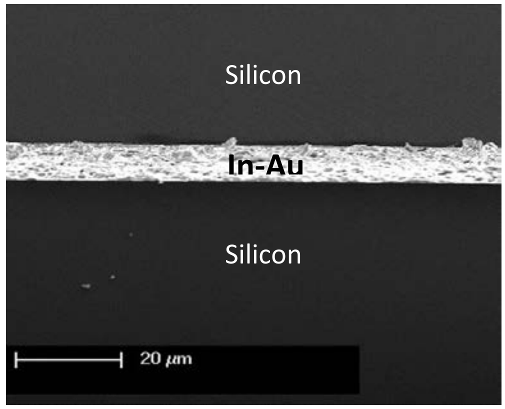

Fig. 3. Result of In-Au bonding process. (a) Bonded silicon pieces. Very good bonding strength has been observed. (b) SEM image of the cross-section of the bonding layer. Uniform In-Au bonding layer has been achieved with no void or peeling.

In order to optimize the device design, advanced multi-junction modeling with luminescent coupling effects has been investigated. In the process of developing the model, the bias-voltage-dependence of luminescent coupling efficiency has been discovered and studied (figure 4). This work will potentially lead to more accurate performance prediction for multi-junction solar cells and greatly improve the cell design process.

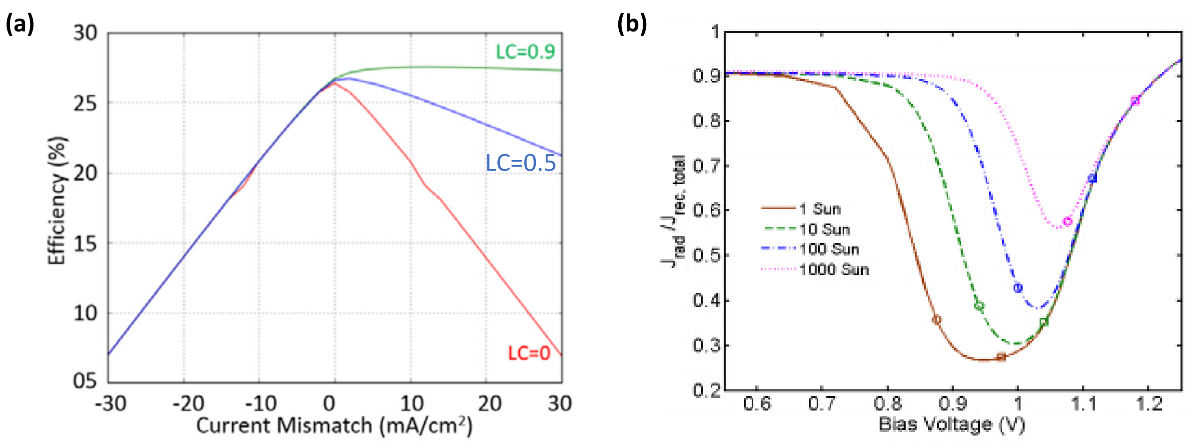

Fig. 4. Modeling results of luminescent coupling effects. (a) Efficiency of a 2-junction solar cell with different photocurrent mismatch of the two junctions. Red, blue and green curves show the cases for luminescent coupling efficiency equal to 0, 0.5 and 0.9 respectively. (b) Change of the luminescent coupling efficiency, expressed as a ratio between the radiative and total recombination current in the top junction, with the bias voltage of the top junction.

Future Work:

The Harris Group will continue to optimize a nanostructured single junction ultra-thin-film GaAs solar cell with a high short circuit current extraction of over 20mA/cm^2 with an overall energy conversion efficiency of over 18%. In order to achieve this, the low-temperature indium bonding process will be integrated into the ultra-thin-film solar cell fabrication process. They'll also fabricate multi-junction solar cells based on ultra-thin nanostructured GaAs and thin c-Si, trying to achieve >30% overall energy conversion efficiency.